The NuMI Off-Axis Experiment

NuHorizons
Fermilab
30 May 2003

Gary Feldman

Formalism

- **Weak and mass eigenstates related by 3 angles and one complex phase:**

$$\left|\nu_\ell\right\rangle = U\left|\nu_h\right\rangle, \quad \text{where} \quad (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Vacuum Oscillations

- **Matter effects: In vacuum,**

$$i\hbar \frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_x\end{pmatrix} = H\begin{pmatrix}\nu_e \\ \nu_x\end{pmatrix}, \quad H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

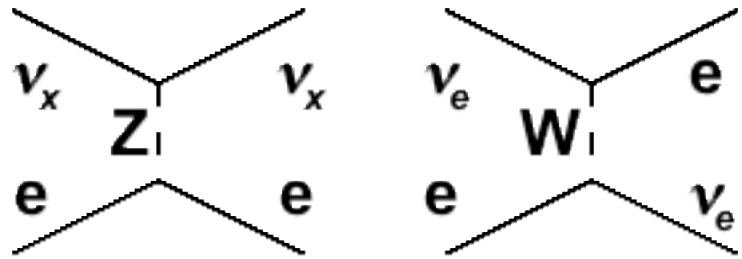
$$P(\nu_e \rightarrow \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ is in } (\text{eV}/c^2)^2,$$

L is in km, and E is in GeV

Matter Oscillations

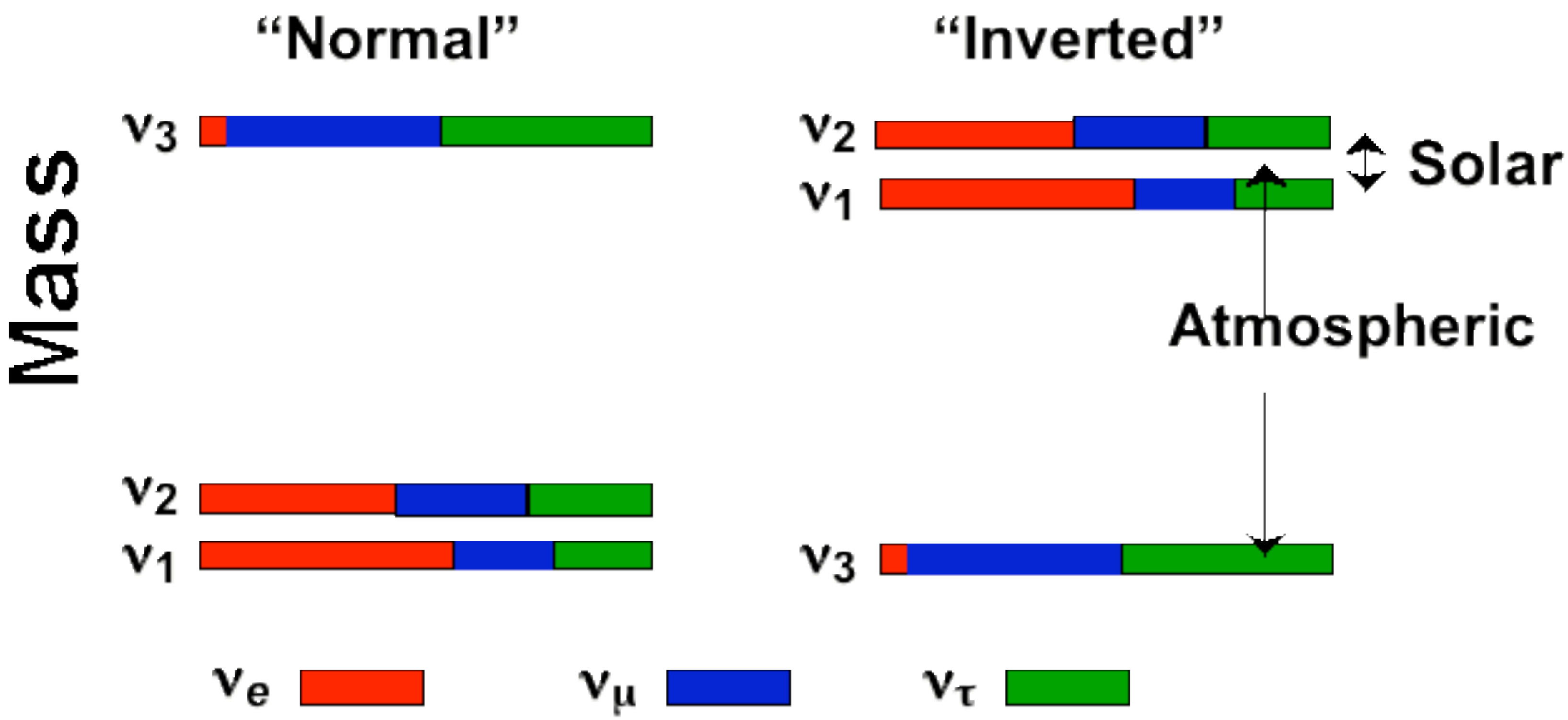
- **Matter effects: In matter ν_e's interact differently than ν_x's.**



$$H = \begin{bmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \sqrt{2}G_F N_e E / \Delta m^2)^2 + \sin^2 2\theta}$$

What Do We Know?



What Do We Want to Know?

- Where we have measurements, we want to improve them.

  $[\sin^2 2\theta_{12}, \sin^2 2\theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}]$

- Where we do not have measurements, we want to obtain them.

  $[\sin^2 2\theta_{13}, \mathrm{sign}(\Delta m^2_{23}), \delta]$

- We want to know if we have the right framework.

  [ν_s, $\beta\beta$ decay, extra dimensions, CPT violation, etc.]

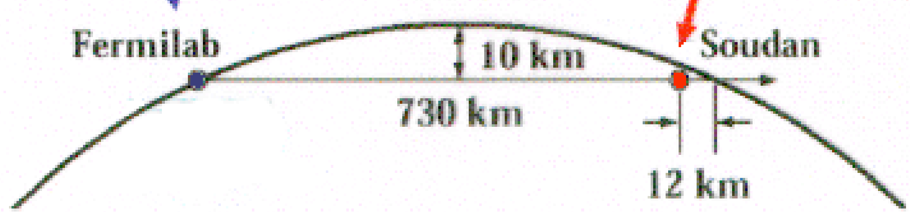
MINOS Layout

(Main Injector Neutrino Oscillation Search)

Two detector oscillation experiment using Fermilab 120-GeV Main Injector beam

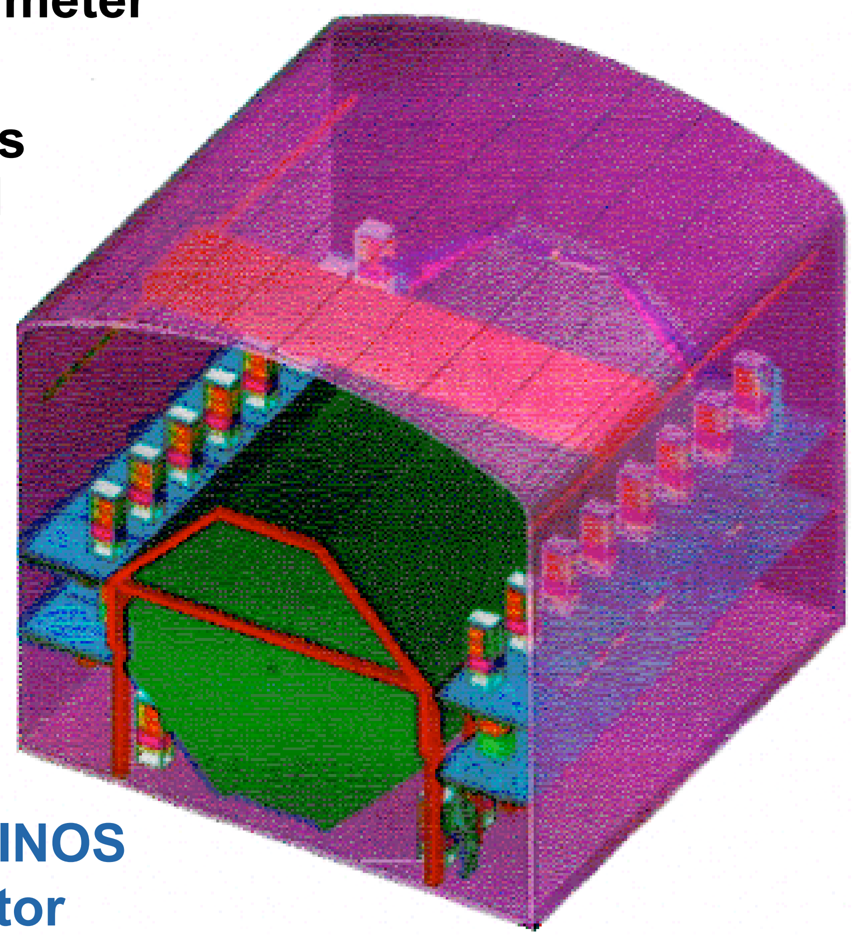
Near detector 980 T at 1 km

Far detector 5400 T at 730 km



MINOS Far Detector

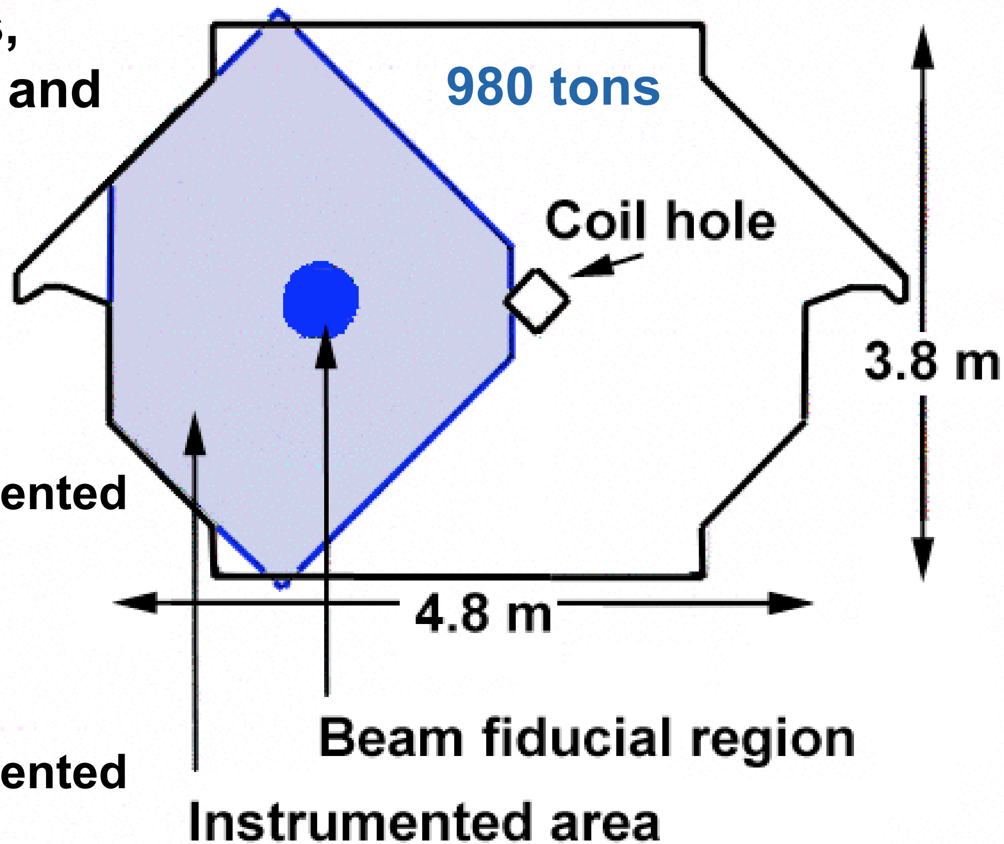
- 8m octagonal tracking calorimeter
- 486 layers of 1 in iron plates
- 4.1 cm-wide scintillator strips with WLS fiber readout, read out from both ends
- 8 fibers summed on each PMT pixel
- 25,800 m^2 (6.4 acres) of active detector planes
- Toroidal magnetic field <B> = 1.3 T
- Total mass 5.4 kT



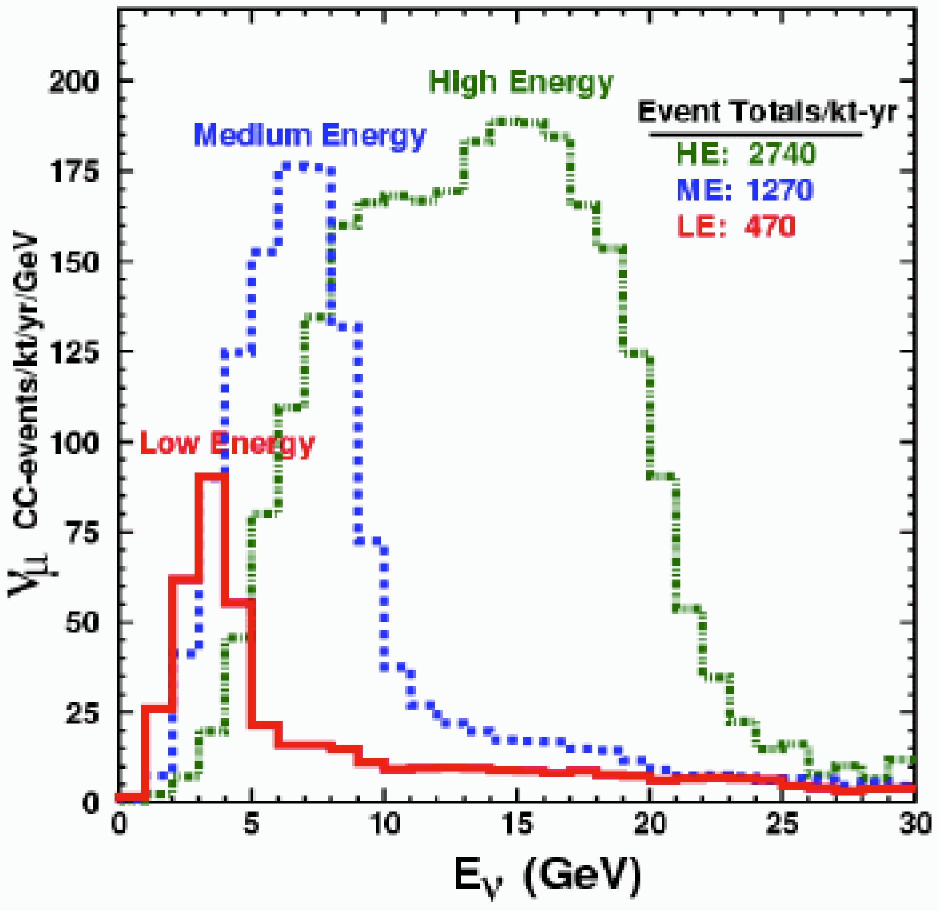
Half of MINOS far detector

MINOS Near Detector

- 280 “squashed octagon” plates
- Same plate thickness, scintillator thickness and width as far detector
- Target/calorimeter section: 120 planes
  - 4/5 partial area instrumented
  - 1/5 full area instrumented
- Muon spectrometer section: 160 planes
  - 4/5 uninstrumented
  - 1/5 full area instrumented



MINOS Energy Options



Different beam energies correspond to different horn currents and positions

Will start with low E beam for best sensitivity to match SK results

MINOS Physics Goals

- **Verify dominant $\square_{\square}$ □ $\square_{\square}$ oscillations**
  - **□appearance is not necessary.**
  - **$\square_{\square}$ CC disappearance with no NC disappearance and no $\square_{e}$ CC appearance □ $\square_{\square}$ □ $\square_{\square}$ oscillations. There is no other possibility.**
- **Precise measurement of dominant $\square m_{23}^{2}$ and $\sin^{2}2\square_{23}$.**
- **Search for subdominant $\square_{\square}$ □ $\square_{e}$ ($\sin^{2}2\square_{13}$) and $\square_{\square}$ □ $\square_{s}$ oscillations.**
- **Study unconventional explanations: neutrino decay, extra dimensions, etc.**

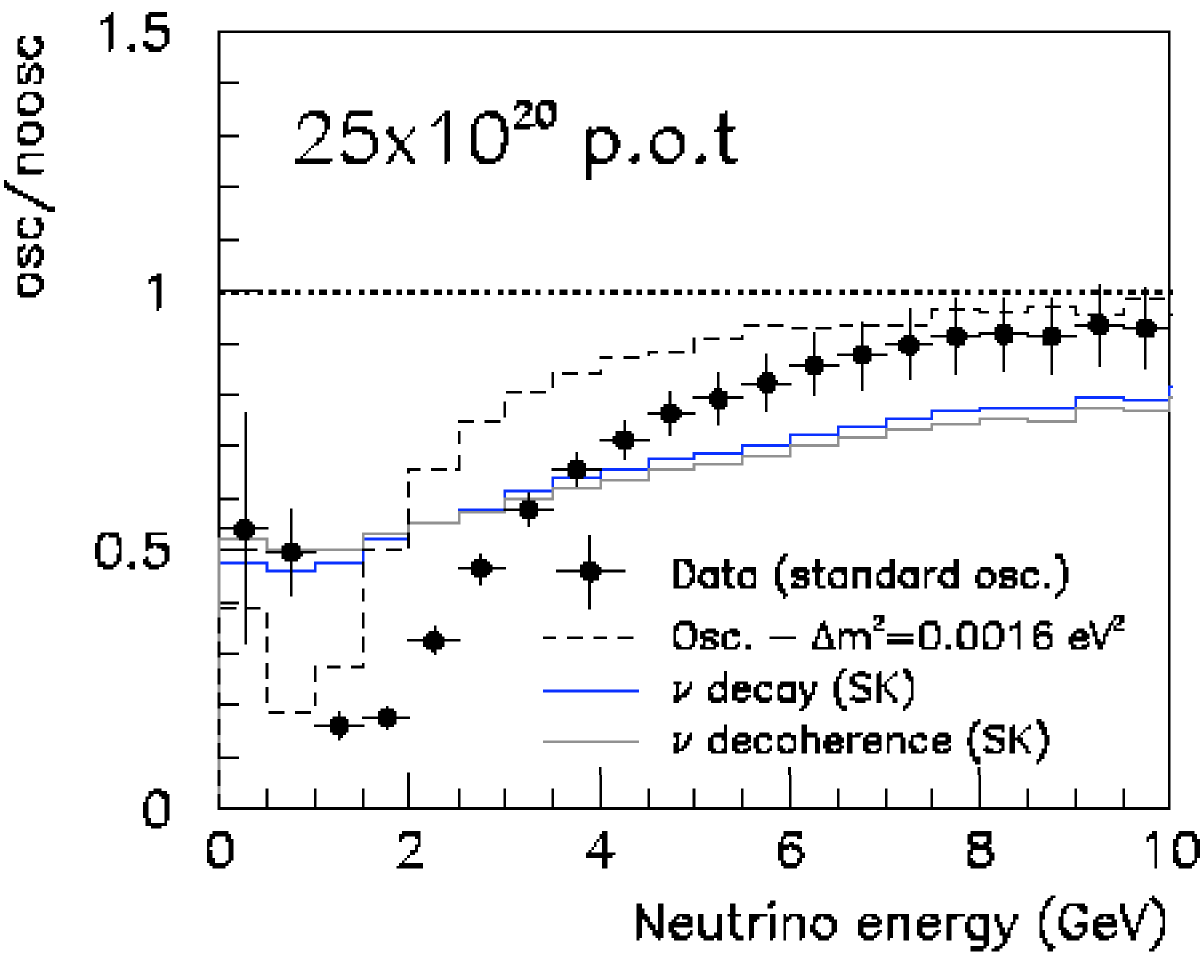
MINOS Physics Tools

- ν_μ CC spectrum
  - Information from both rates and shape. The latter is independent of the near / far normalization.
- NC / CC ratio
  - Independent of the near / far normalization .
- ν_e CC appearance
  - Use topological criteria: fraction of energy in first few radiation lengths, shower asymmetry, etc.

NuMI Beam Intensity

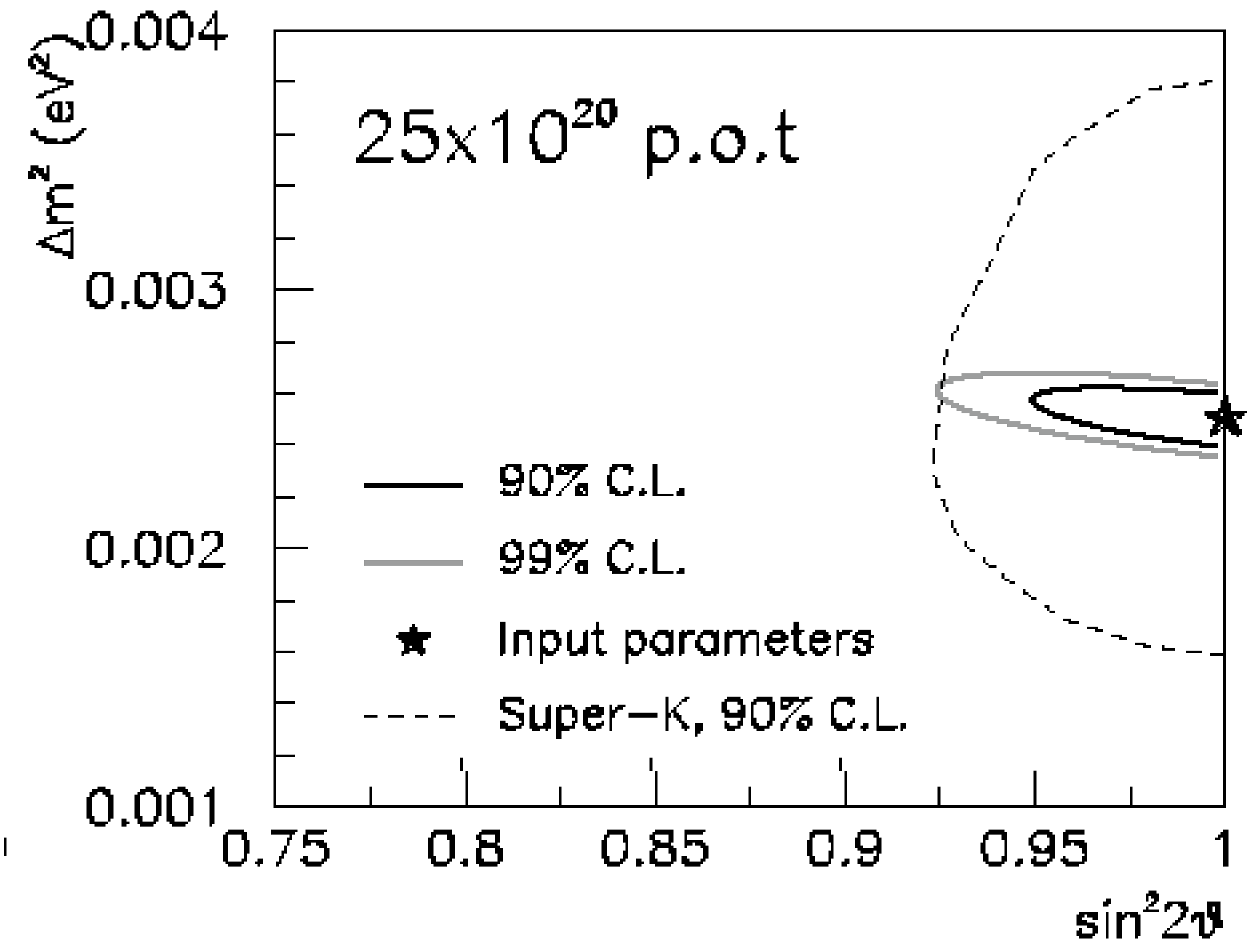
- MINOS proposal calls for 2 yrs of running at 3.7×10^{20} pot = 7.4×10^{20} pot
- We are proposing that Fermilab spend ~10M$/yr to upgrade the beam intensity to 7.2×10^{20} pot by 2009, yielding 25×10^{20} for a 5 yr run beginning in 2005.
- This can possibly be achieved by multi-bunch stacking in the MI and faster cycle times with increased magnet and RF power. Issues being studied by the Finley Committee.

MINOS CC Measurements

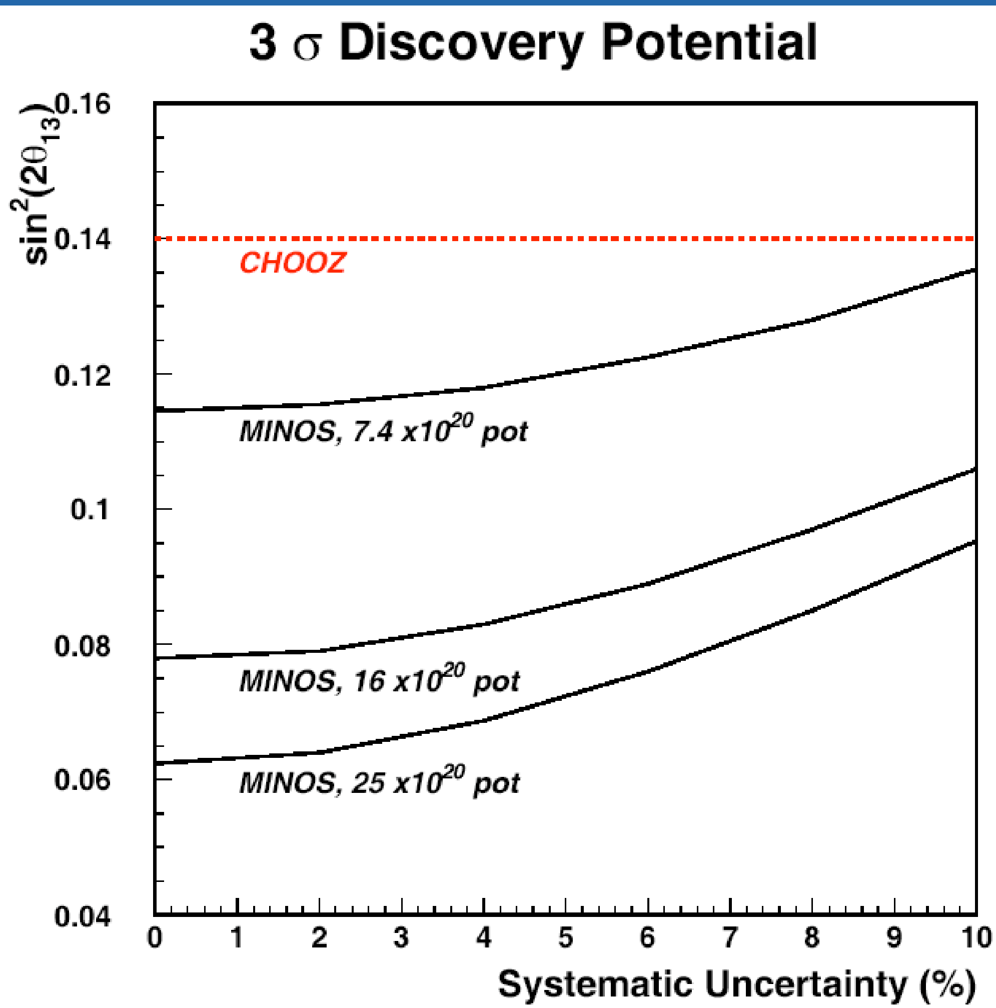


MINOS Sensitivity to

□ □ □

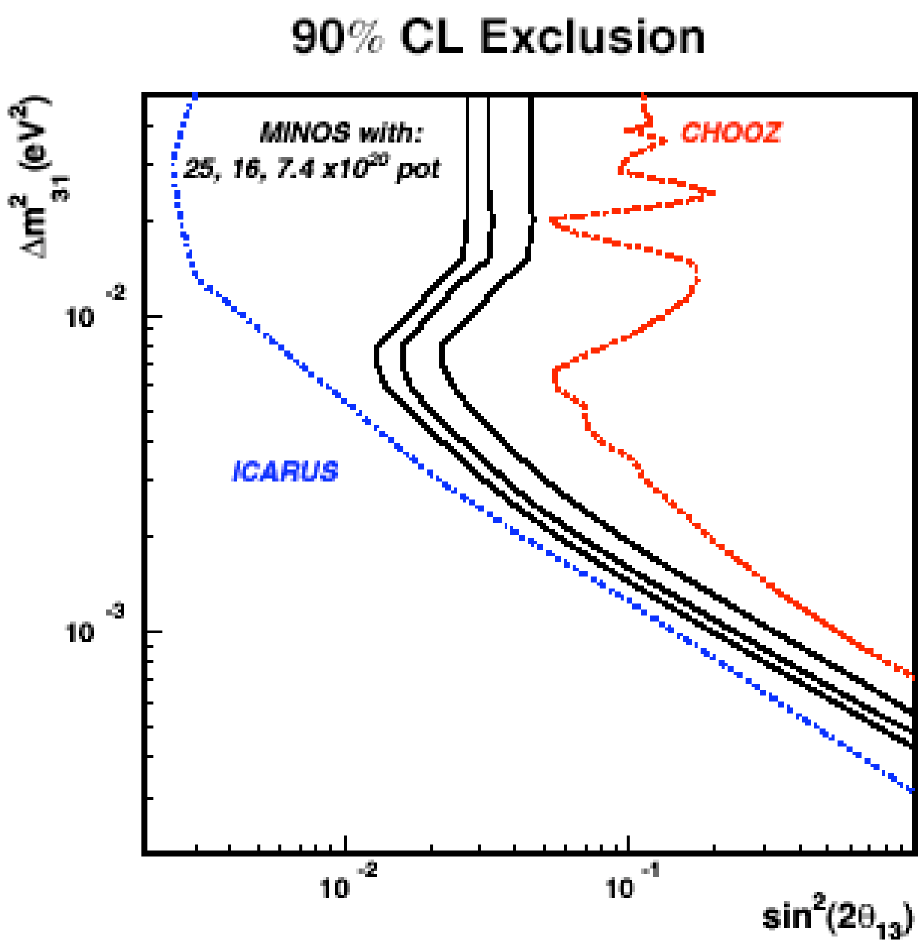


MINOS Sensitivity to $\nu_\mu \to \nu_e$ vs. Systematic Errors



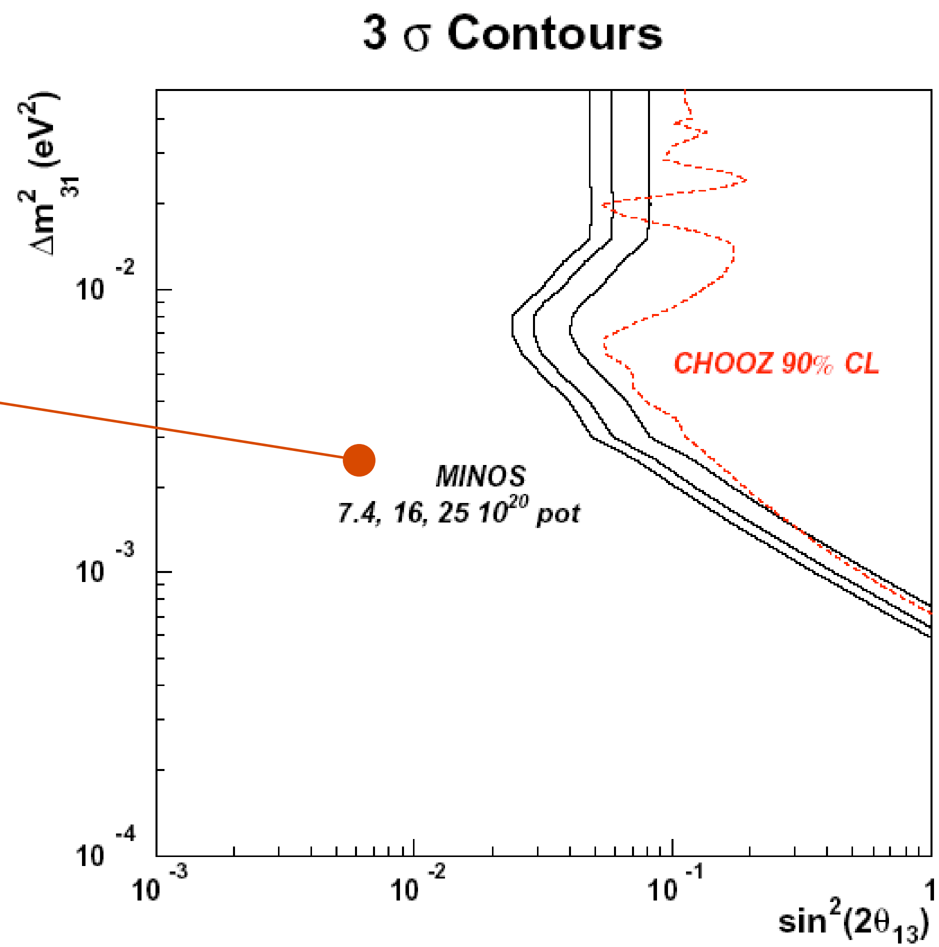
Δm^2 = 0.0025 eV^2

MINOS Sensitivity to $\nu_\mu \rightarrow \nu_e$ at 90% CL



MINOS Sensitivity to $\nu_\mu \to \nu_e$ at 3σ Discovery

Off-Axis Goal



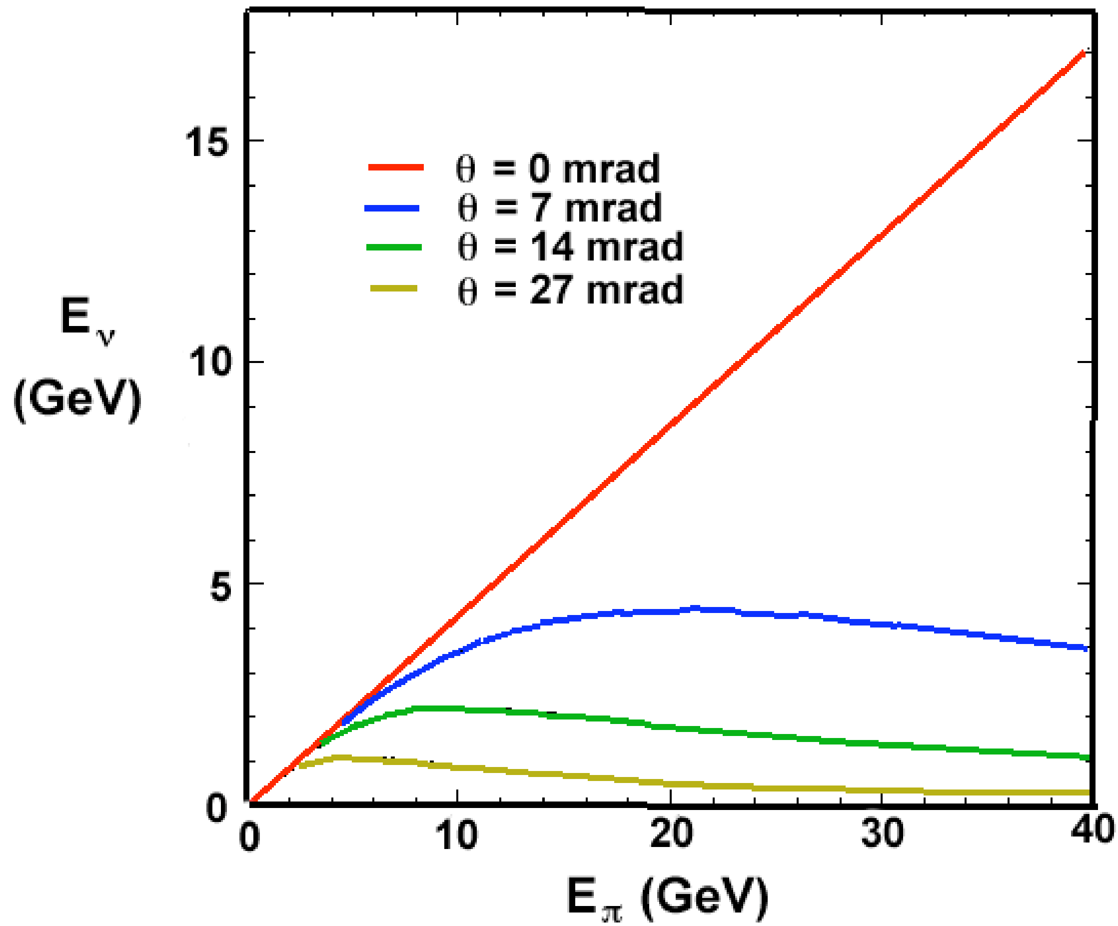
Off-Axis Beams

- It is clear that the next generation of experiments will concentrate on $\nu_e \leftrightarrow \nu_\mu$ oscillations -- needed for
  - $\sin^2 2\theta_{13}$
  - $\mathrm{sign}(\Delta m^2_{23})$
  - δ

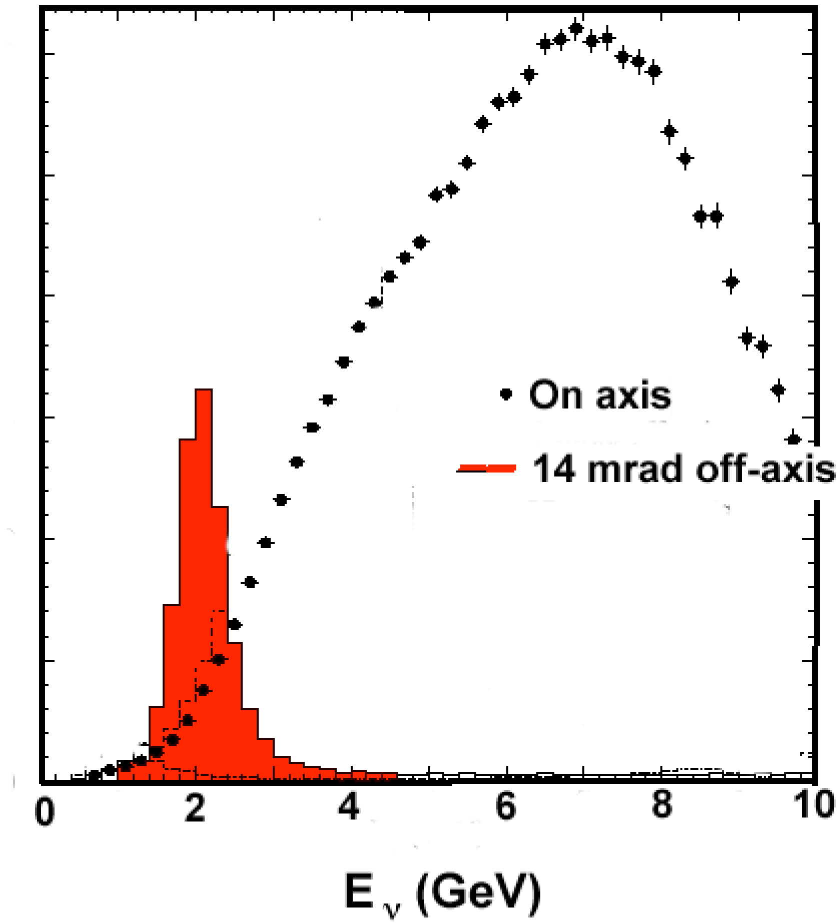
Off-Axis Rationale

- Want low-energy narrow-band beams at $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum:
  - ν_e appearance maximum
  - ν_μ CC disappears
  - Higher-energy NC disappears
- Want detectors optimized for ν_e detection
- Want increases in beam flux times detector mass
- $\Rightarrow$ Off-axis Experiment Proposal

Off-Axis Kinematics



Off-Axis Spectrum (No oscillations)



Off-Axis Physics (In Vacuum)

- Assume that we will always work at the $\Delta m^2_{13} \approx \Delta m^2_{23}$ oscillation maximum, so that $1.27\,\Delta m^2_{13} L / E = \pi/2 + n\pi$.

- Assume that $\sin^2 2\theta_{23} \approx \sin^2 2\theta_{12} \approx 1$.

- Then the leading term for $\nu_\mu \to \nu_e$ oscillations is

$$P_{vac}(\nu_\mu \to \nu_e) \approx \frac{1}{2}\sin^2 2\theta_{13}$$

Off-Axis/Super Beam Physics (In Matter)

- In matter,

$$P_{mat}(\nu_\mu \to \nu_e) \approx \left(1 \pm \frac{2E}{E_R}\right) P_{vac}(\nu_\mu \to \nu_e),$$

where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2} G_F \rho_e} \approx 11 \text{ GeV for the earth's crust.}$$

$\Rightarrow$ ~30% effect for NuMI, ~10% effect for J-PARC at the first oscillation maximum.

Off-Axis Physics (CP Violation)

- The next leading term is CP violating:

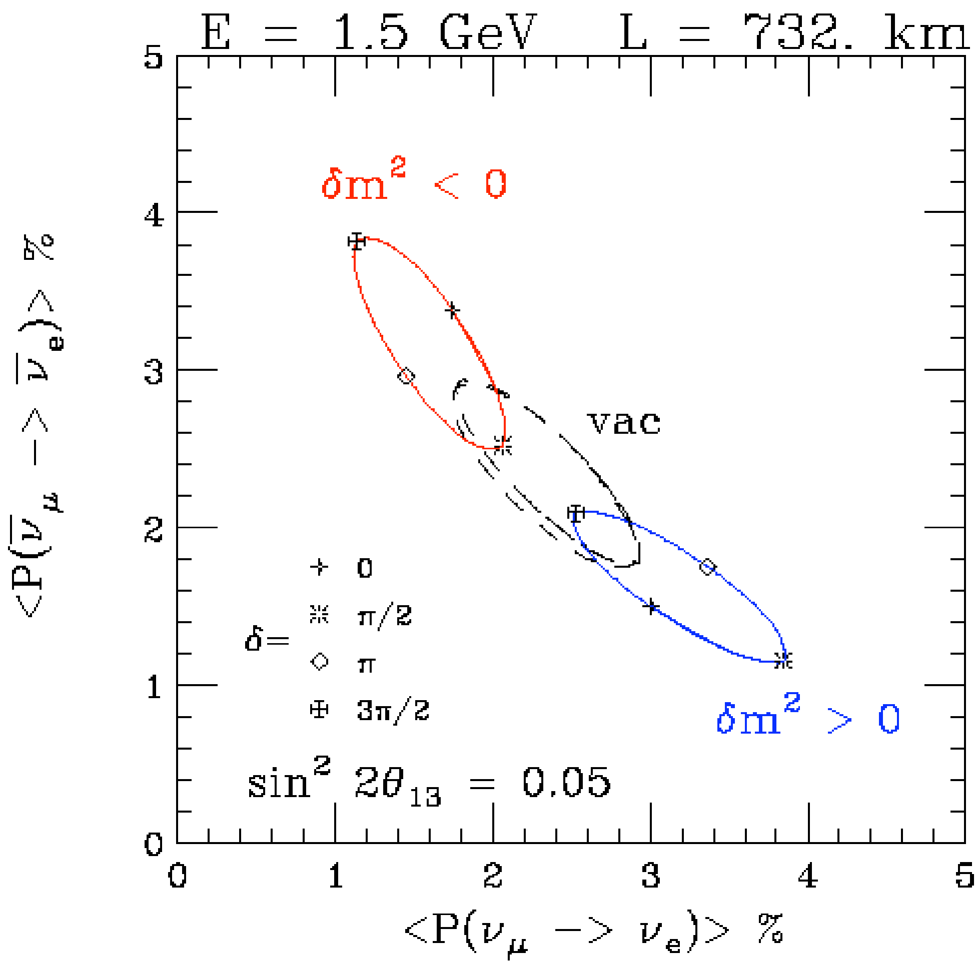
$$P_{CP}(\nu_\mu \to \nu_e) \approx \pm J \sin\left(\frac{1.27\,\Delta m^2_{12} L}{E}\right),$$

where $J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \approx \sin 2\theta_{13}$,

and where the top sign is for neutrinos and the bottom sign is for antineutrinos.

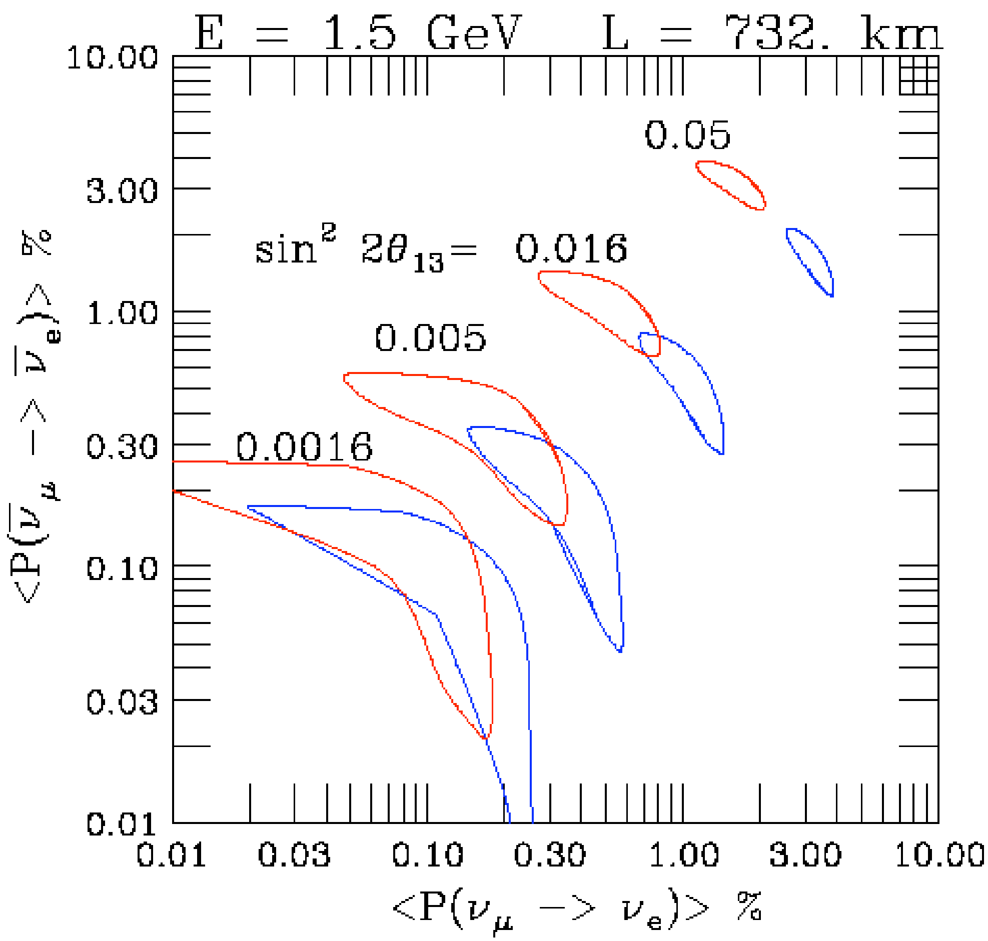
- For a single set of measurements, there can be ambiguities between the matter effect and CP violation.

NuMI Off-Axis
Neutrino vs. Antineutrino (1)



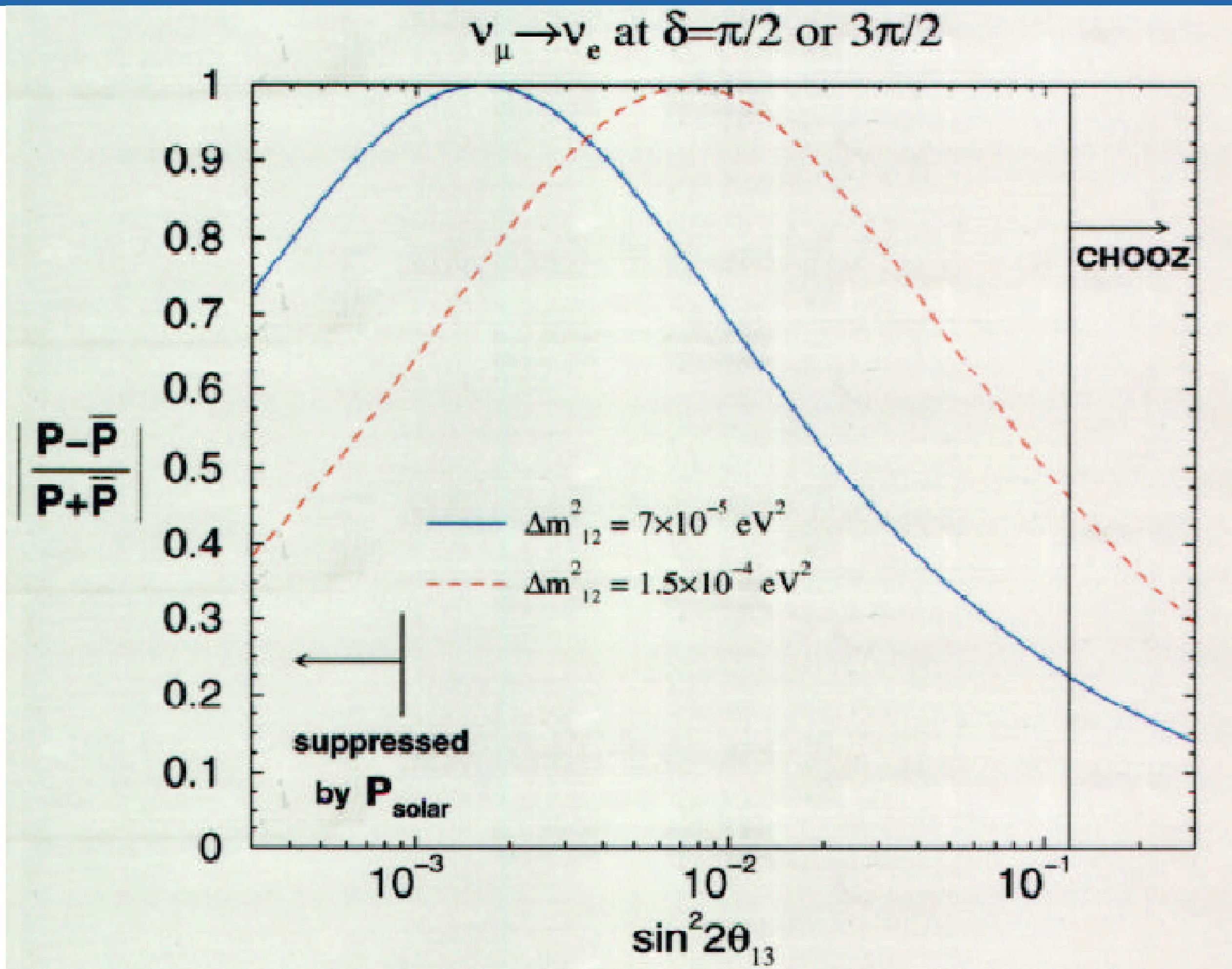
$$\Delta m^2_{12} = 5 \times 10^{-5}\ (\mathrm{eV})^2$$

NuMI Off-Axis
Neutrino vs. Antineutrino (2)



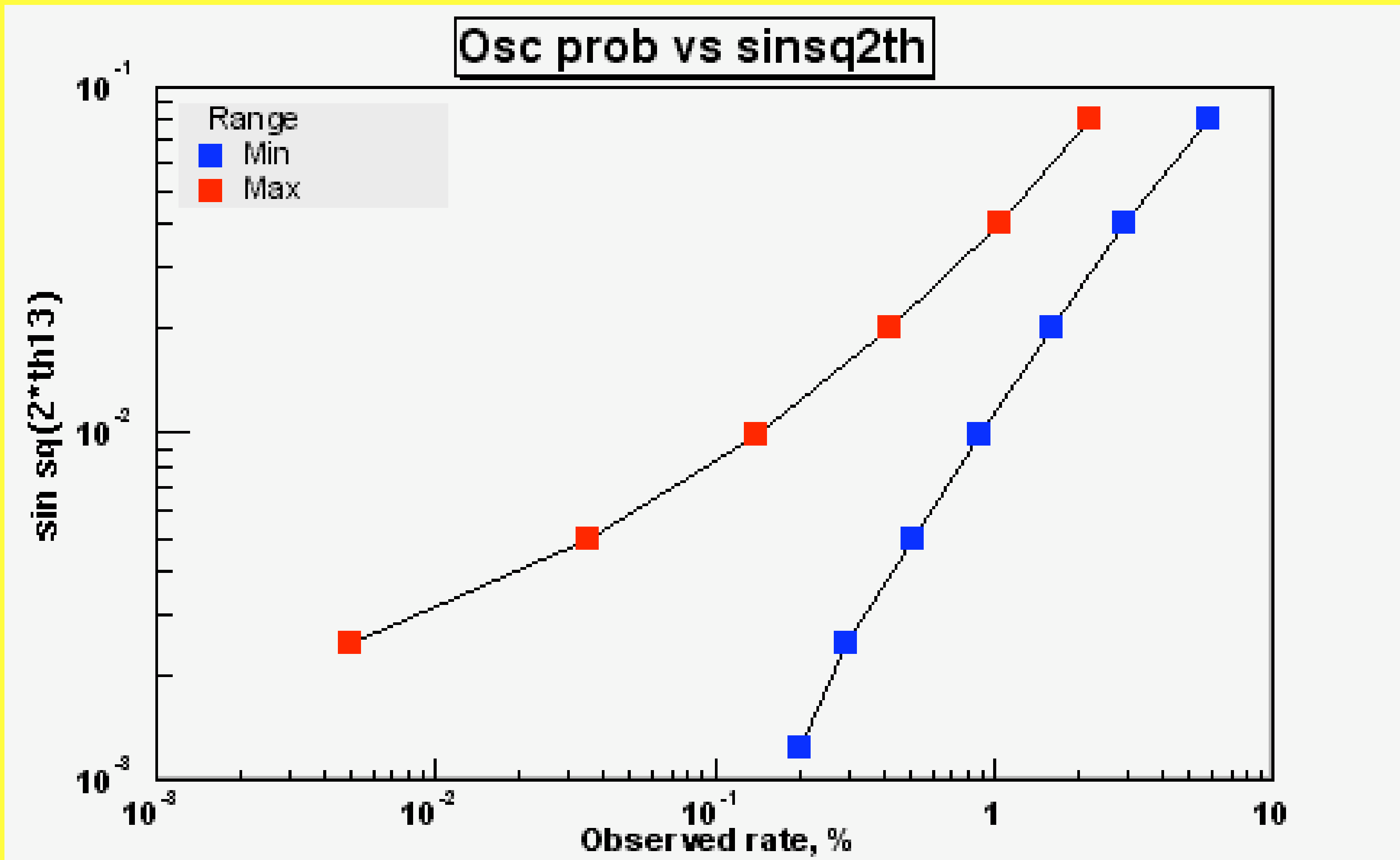
$\Delta m^2_{12} = 5 \times 10^{-5}\ (\mathrm{eV})^2$

CP Asymmetries are Large



from
S. Parke

Ambiguities in $\sin^2(2\theta_{13})$ Measurement



Determining the Mass Hierarchy

- The effect is binary.
- Three ways of resolving it:
  - Run at both 1st and 2nd oscillation maxima (2nd maximum has 1/3 matter effect and 3 CP effect, but rate at 2nd maximum very low)
  - Run neutrinos and antineutrinos (antineutrinos have ~1/3 the rate)
  - Run at two different baselines -- i.e., take advantage of the complementarity of NuMI and J-PARC (~3 x the matter effect at NuMI) or the complementarity of NuMI and a reactor experiment.

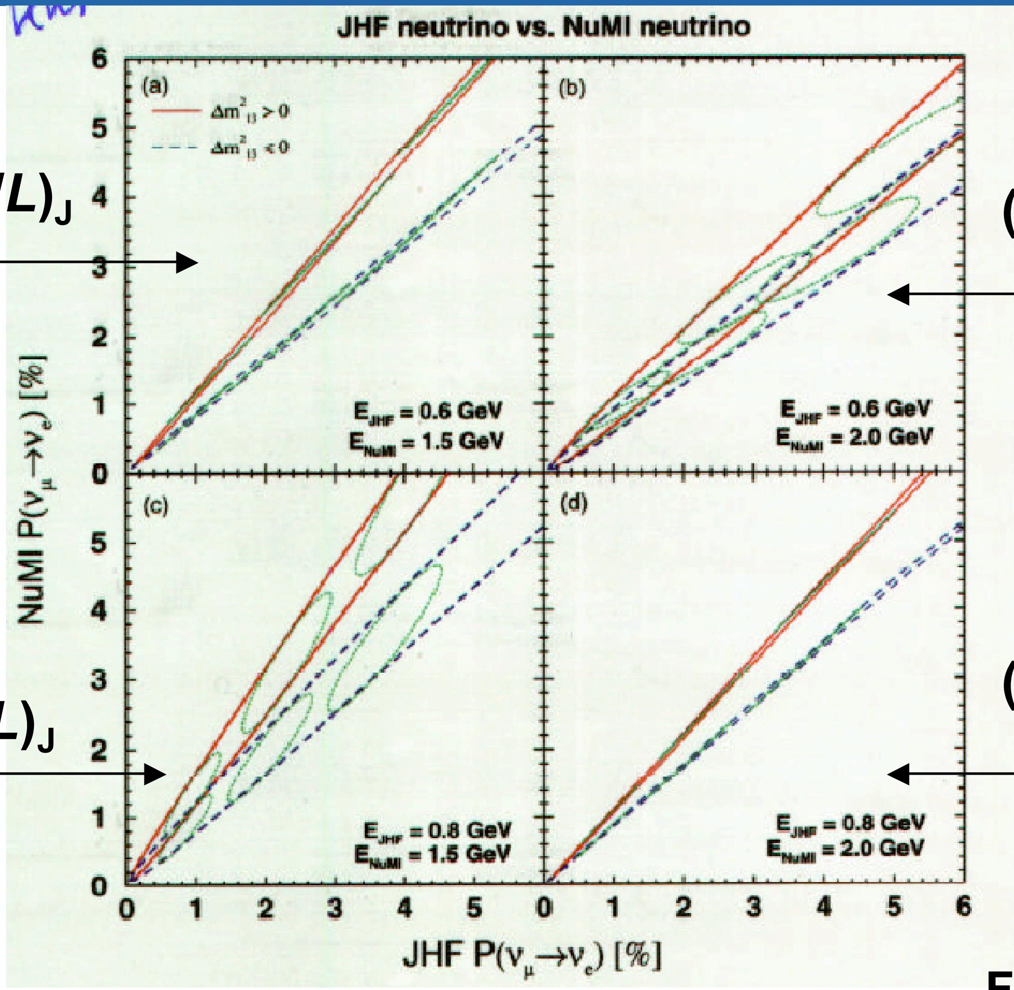
$(E/L)_{NuMI} \leq (E/L)_{J\text{-}PARC}$ for Complementarity

$(E/L)_N = (E/L)_J$

Best

$(E/L)_N \geq (E/L)_J$

Bad



$(E/L)_N \leq (E/L)_J$

OK

$(E/L)_N = (E/L)_J$

Best

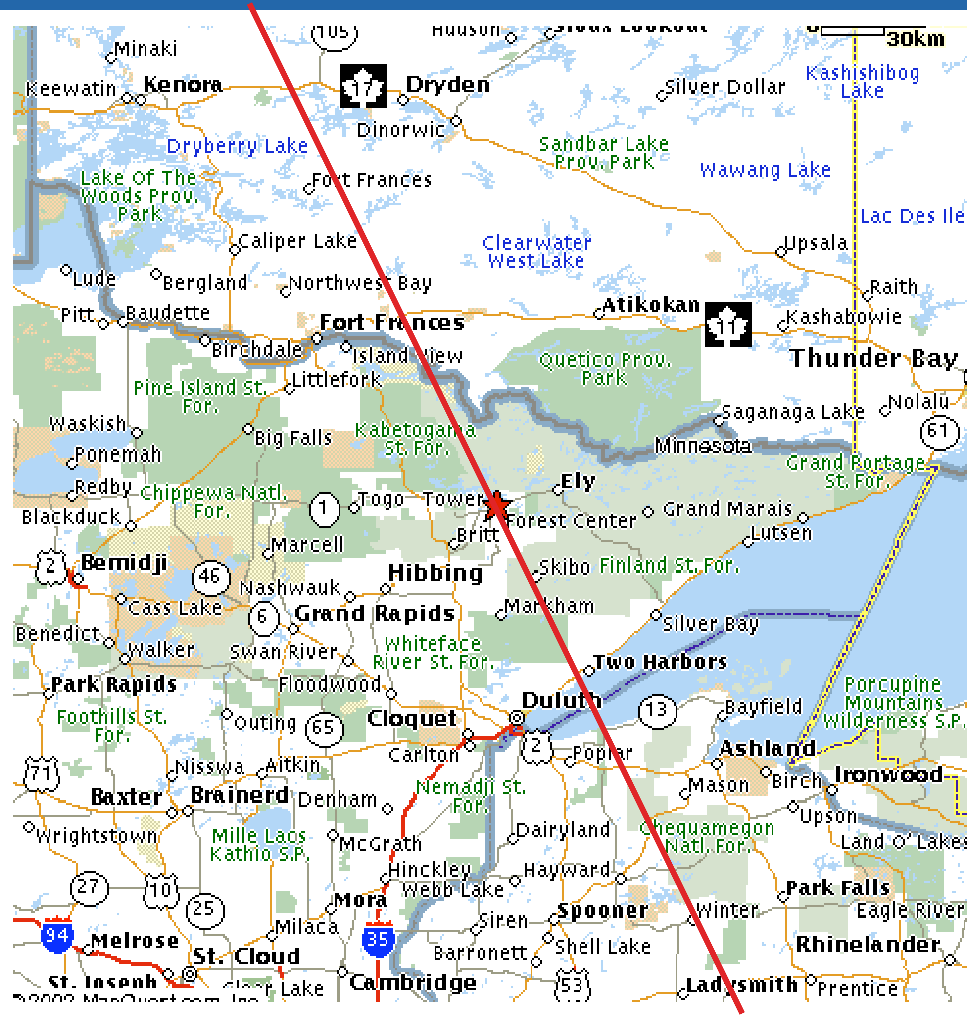
From S. Parke

Determining the CP Phase

- Since □ depends only on *L*/*E* at each oscillation maximum, it must be determined by either
  - Energy dependence or
  - Antineutrino run

Where should the off-axis experiment be sited?

Want a site about 10 km off the beam line, so there is a large ellipse of possible sites.

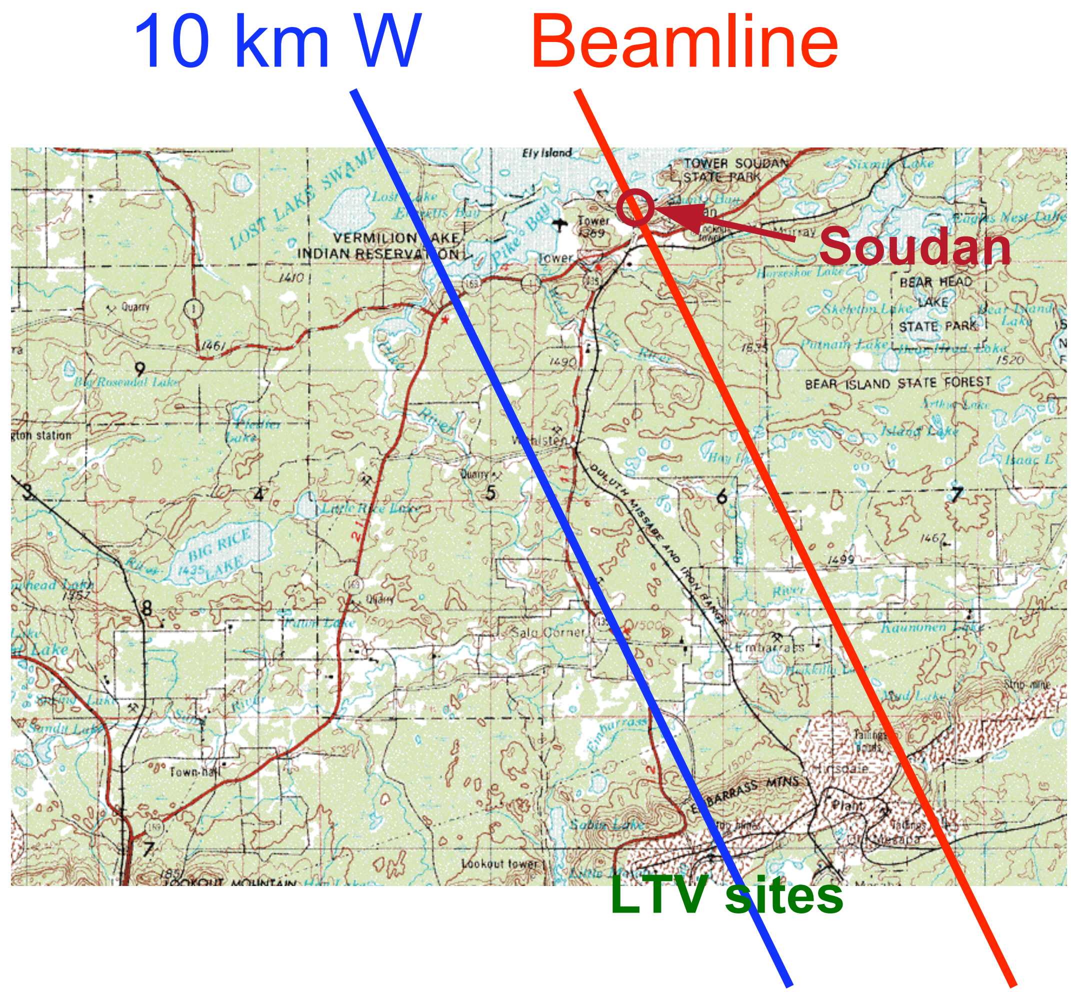


LTV Site 712 km

Former surface mining site, no longer used.

Large site, 25 by 5 miles.

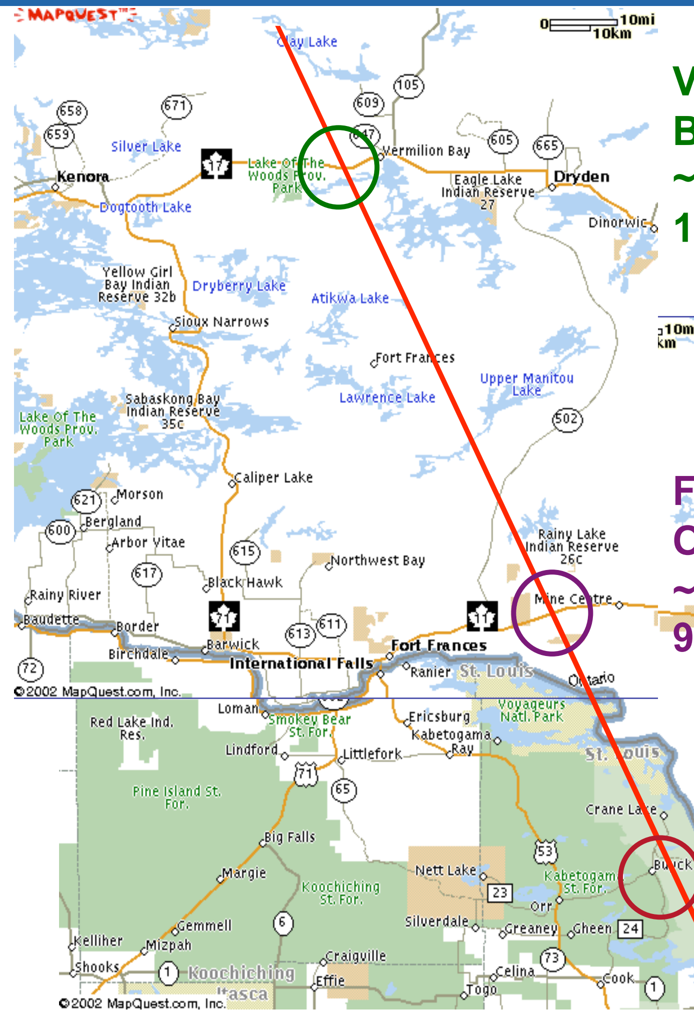
Road and rail access. Power, fiber, and cell phone.



Longer Baseline Sites

All sites have power and road access.

Buyck and Vermillion Lake have a nearby gas station and bar.



Vermilion Bay, Ontario
~950 km,
15.6 km up

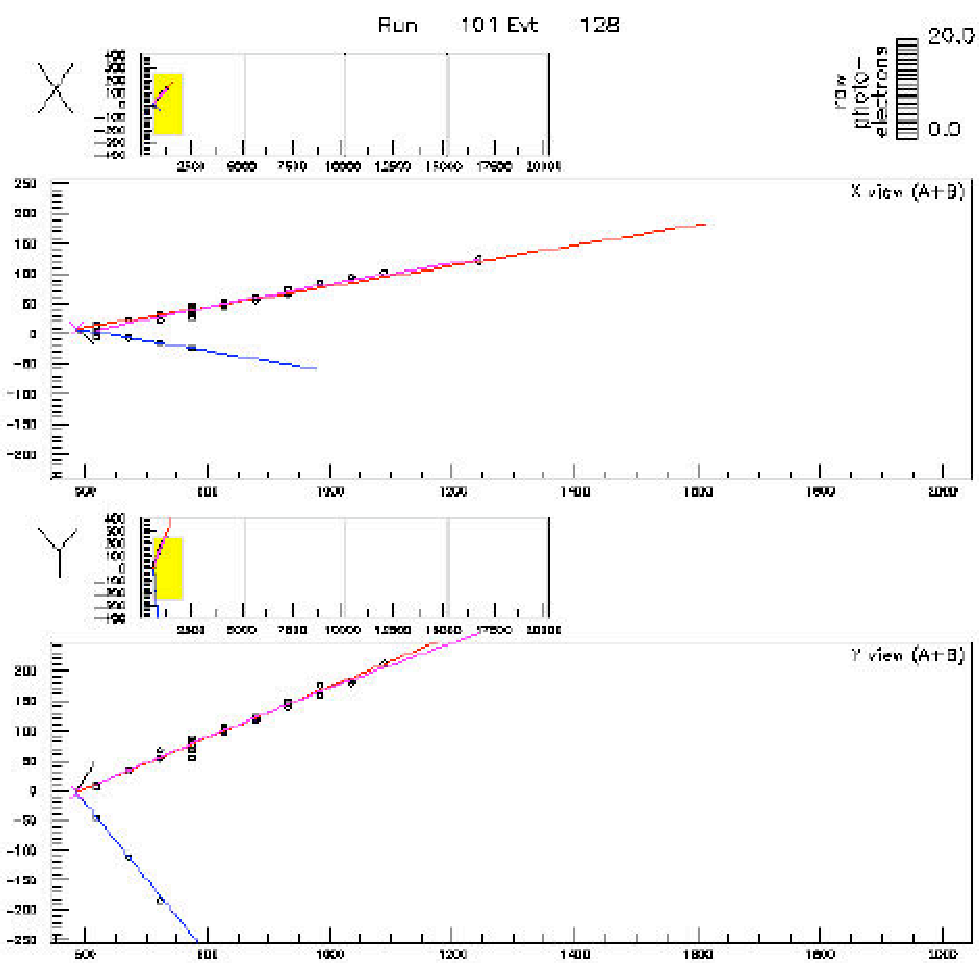
Fort Frances, Ontario
~875 km,
9 km up

Buyck, MN
775 km,
2 km up

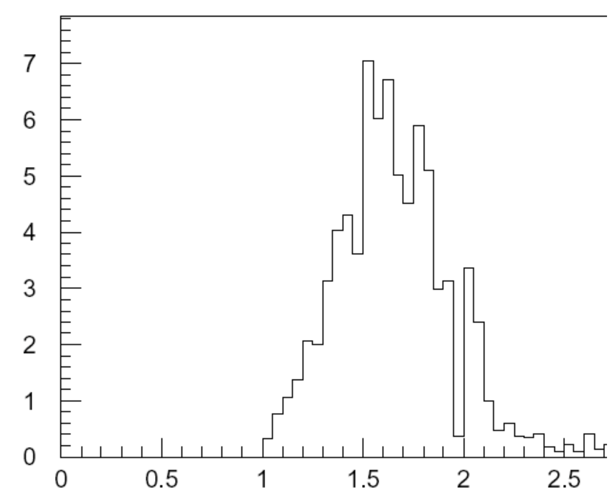
Detector Technology Choice

- Most troublesome backgrounds are asymmetric π^0 decays from NC and ν_μ CC events where the muon is not detected.
- H_2O Cerenkov detectors do not provide optimum rejection for *E* > 1 GeV.
- Best rejection is given by liquid argon detectors, but required R&D is not compatible with the envisioned time scale.
- Next best option is highly-segmented (~1/3 X_0) medium-Z sandwich detectors.

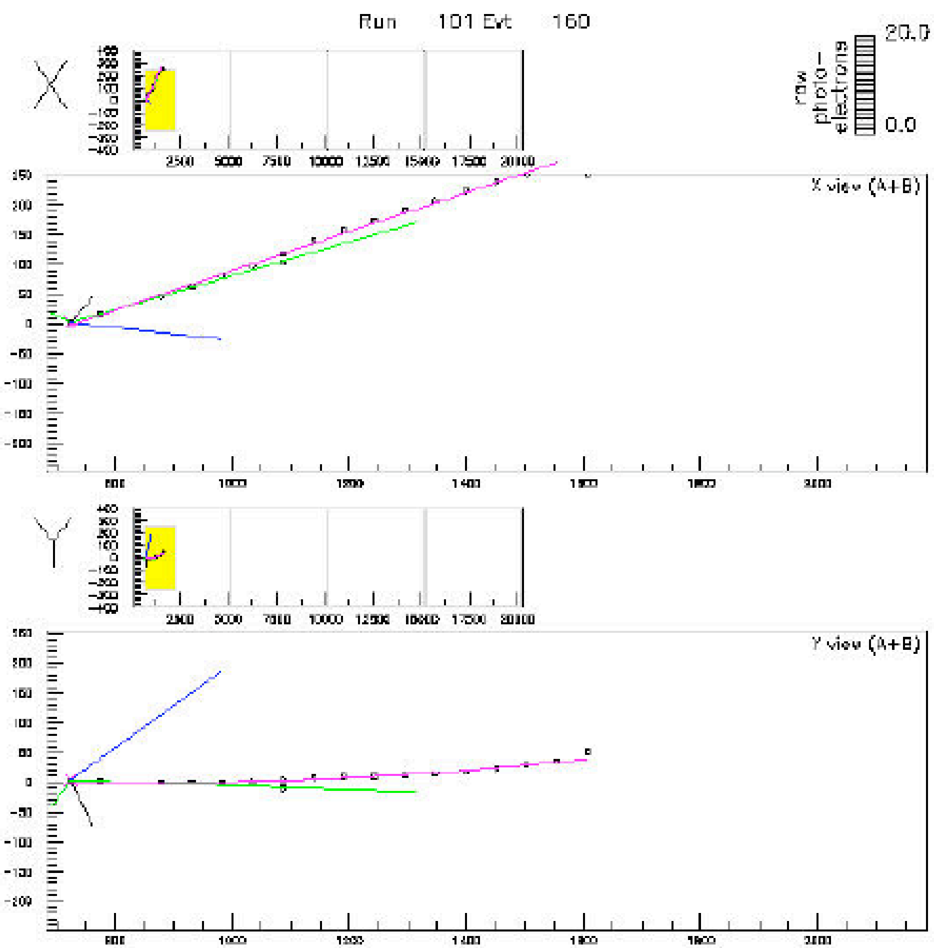
Electron Track



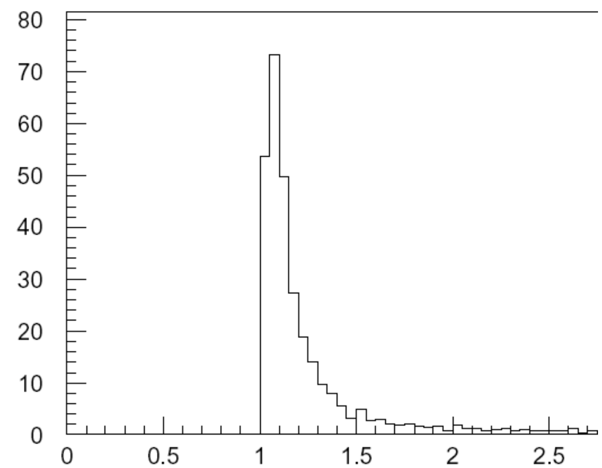
Hits per plane > 1



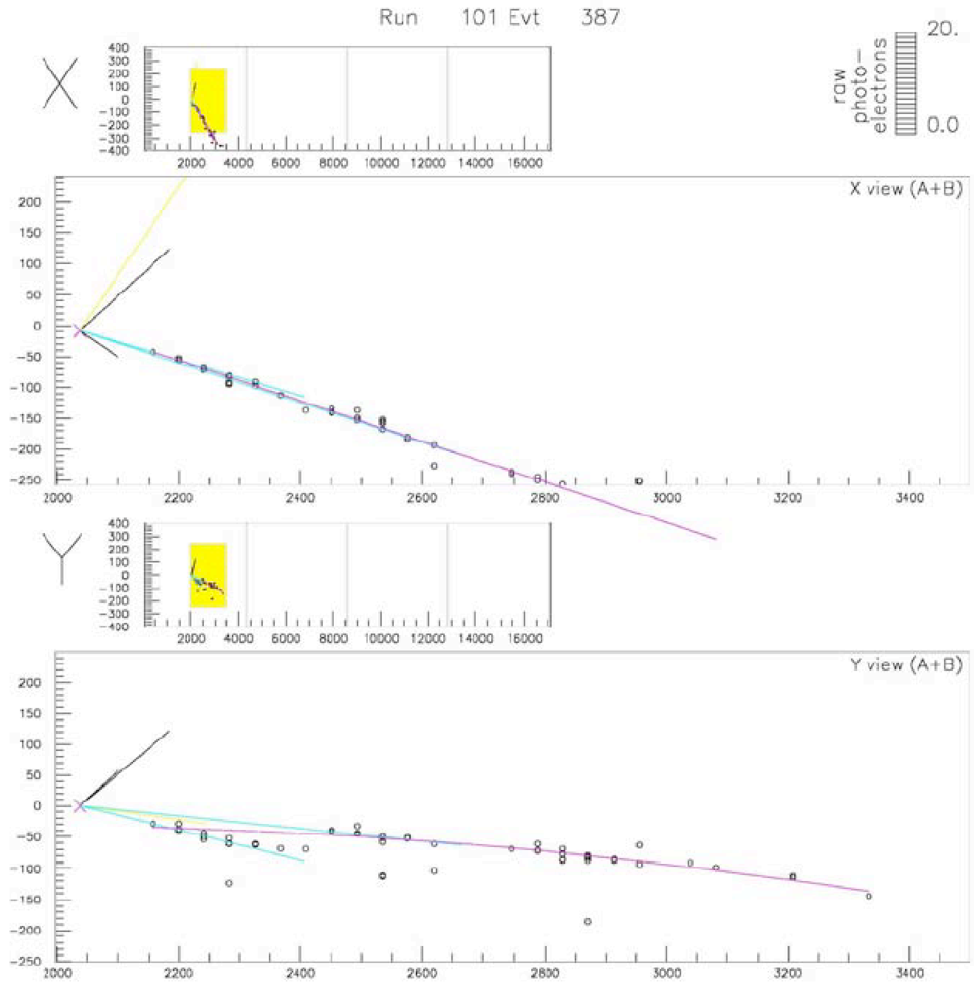
Muon track



Hits per plane ~1

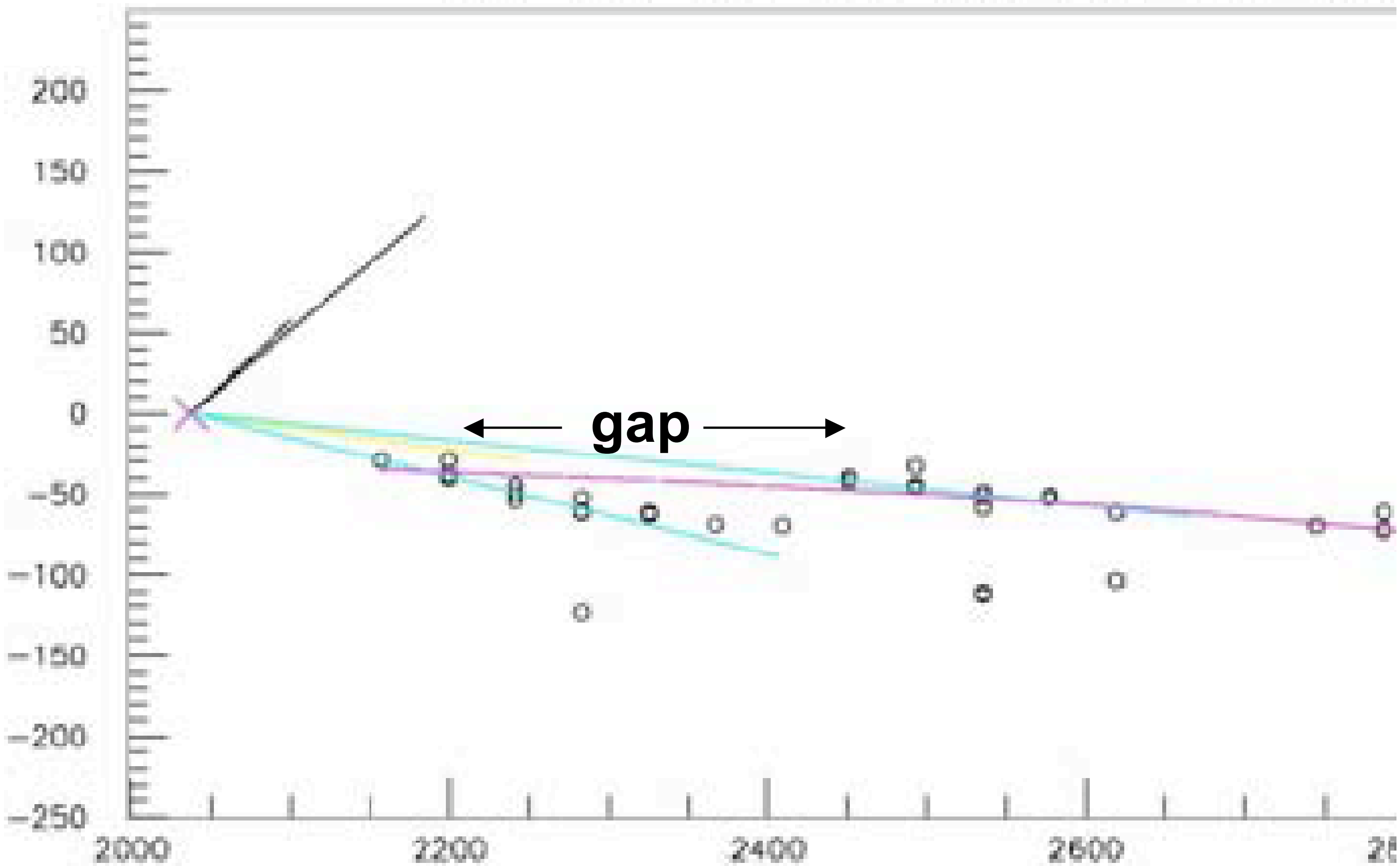


NC with leading π^0



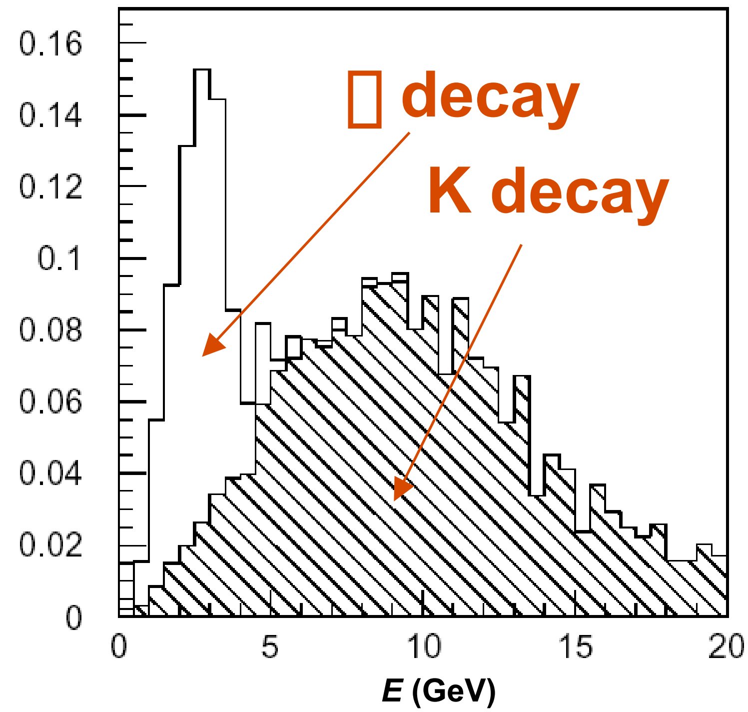
Two tracks with different starting points leading to a “gap”

Detail of NC with leading π^0



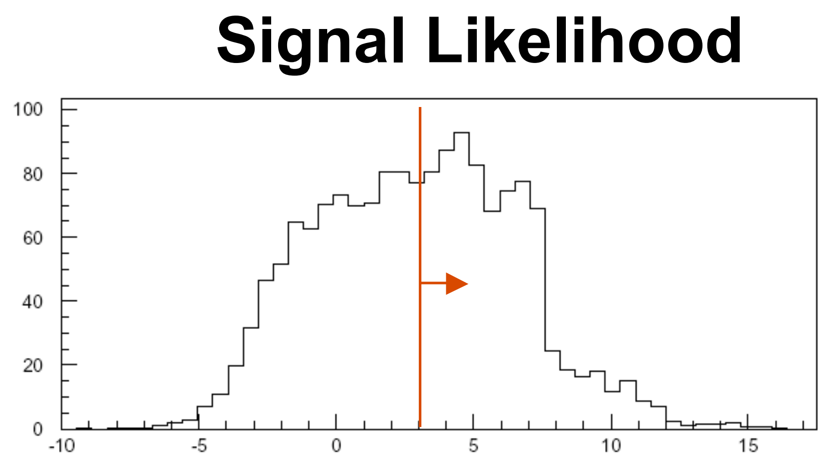
Backgrounds: Beam ν_e

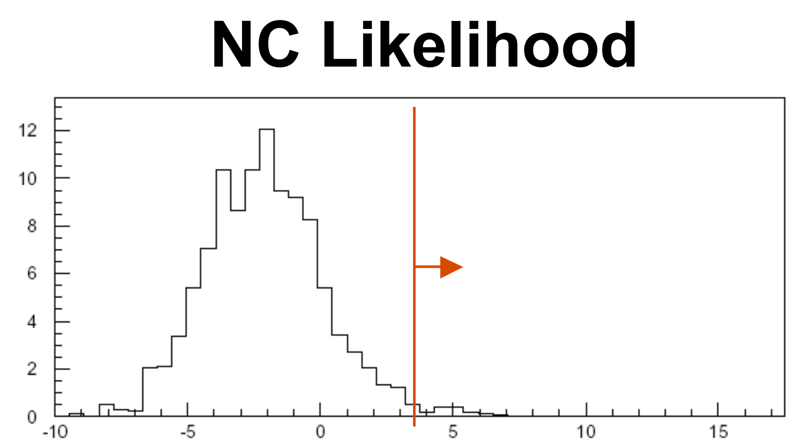
- **54% of eventual background**
- **Mostly from muon decay**
  - **Calculable from near detector ν_μ CC events**
  - **Measurable in the near detector**



Backgrounds: NC

- 34% of eventual background
- Rejected by a likelihood analysis based on topological parameters





Backgrounds: ν_μ CC

- 12% of eventual background
- Hugely overestimated in the near detector
- Need a good understanding of NC/CC ratios and efficiencies
- Can study misidentification efficiency by removing identified muons from CC events.

Backgrounds: □□ CC

- **Negligible since we work below □threshold.**

Detector Technology: Absorber

- Consensus to use particle board
  - Structural material
  - Manufactured in 24 by 8 ft lengths
  - Density 0.6 g/cm^3, but can be increased
  - Cost \$0.31/kg
  - There are thermal and hydroscopic issues that appear solvable.

Detector Technology: Active Elements

- Scintillators (à la MINOS) and RPCs (à la BELLE) under consideration.
- Scintillators
  - Well-understood technology
  - One-ended digital readout (cheap electronics)
  - 64-pixel PMT or APD photon detectors
- RPCs
  - Reliable (No failures at BELLE in 5 yrs.)
  - Inexpensive
  - X and Y readout on each chamber

Detector Packaging

- Monolithic and containers being considered
- Containers
  - Pre-engineered
  - All assembly at detector factories
  - Con: Extra gaps and material

How Do We Decide These Issues?

- Committees
  - TESCOE: TEchnical Steering Committee for the Off-axis Experiment (GF chair)
  - CostCom: Costing Committee (Gina Rameika chair)
- Criterion:
  - For a fixed physics goal, we want to recommend the reliable technologies that are the least expensive.
  - We are studying the optimizations and engineering issues.

Timetable: History and Short Term

- LOI submitted August 2002 (P929)
  - Kind words of support from the PAC
- Workshops:
  - Stanford January 2003
  - Argonne April 2003
  - Fermilab July 10-12, 2003
  - Fermilab September 11-13, 2003
- Off-axis concept presented to the HEPAP HEP Facilities Panel, February 2003
  - Ranked “Important”
- Intention to submit a proposal for the November 2003 PAC meeting.

Timetable: Possible Longer Term Schedule

- **June 2004: PAC approval for a near detector**
- **2004-2006 Near detector construction and running and far detector engineering**
- **2006 Start of far detector construction**
- **2009 Start of full run**
- **Note: The beam will exist and the detector is modular. The experiment can start prior to full completion.**

Signal and Backgrounds: NuMI Off-Axis and J-PARC

$\sin^2(2\theta_{13})_{eff} = 0.1$

	NuMI Off-axis 50 kton, 85% eff, 5 years, 4×10^{20} pot/y		JHF to SK Phase I, 5 years	
	all	After cuts	all	After cuts
ν_μ CC (no osc)	28348	6.8	10714	1.8
NC	8650	19.4	4080	9.3
Beam ν_e	604	31.2	292	11
Signal (Δm^2_{23}=2.8/3 x 10^{-3}, NuMI/JHF)	867.3	307.9	302	123
FOM (signal/$\sqrt{\text{bckg}}$)		40.7		26.2

3 σ Discovery Limit for $\sin^2(2\theta_{13})_{eff}$

- Assume $\Delta m_{23}^2 = 2.8\times10^{-3}$ eV^2 and 5% systematic error on the backgrounds
- 5 yr at 4×10^{20} pot/yr x $\sin^2(2\theta_{13})_{eff} \geq 0.008$
- 5 yr at 7.2×10^{20} pot/yr x $\sin^2(2\theta_{13})_{eff} \geq 0.006$

Conclusion

- The Off-Axis Experiment will be a powerful second phase in the Fermilab neutrino program.